The Effect of Load VSWR on the Performance of Ferrite Phase Shifters

M. L. Reuss, Jr.

Microwave Antennas and Components Branch
Electronics Division

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NAVAL RESEARCH LABORATORY
Washington, D.C.

ABSTRACT

When the beam of a phased-array antenna is scanned, the power coupled back toward the source from the radiating elements varies in phase and magnitude. This coupled power appears to a phase shifter located between the source and the radiating element as a variable-mismatch termination. When ferrite phase shifters are employed at high peak power levels, an additional complication arises due to the nonlinear loss characteristic of the ferrite material. This report describes the effect of given load mismatches on the performance of three different model S-band ferrite phase shifters as the incident peak power level is varied.

PROBLEM STATUS

This is an interim report; work continues on other phases of the problem.

AUTHORIZATION

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THE EFFECT OF LOAD VSWR ON THE PERFORMANCE OF FERRITE PHASE SHIFTERS

INTRODUCTION

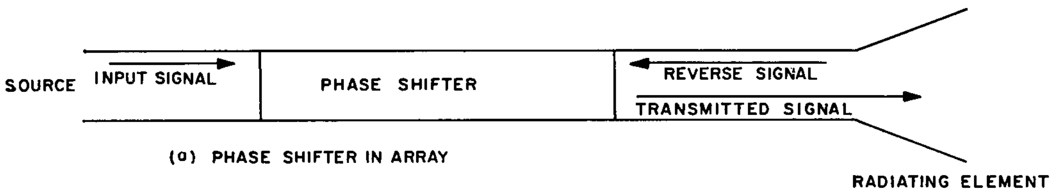
The Navy requires modern radar systems which can scan very rapidly in order to detect and track high-speed missiles and aircraft. Such beam scanning can best be accomplished by electronic means as typified by an array of radiating elements where each element is preceded by a phase shifter. Due to mutual coupling between radiating elements, different amounts of power are often coupled back through the phase shifter as the array scan angle is changed. The effect of this coupled power is to change the phase and amplitude of the radiated signal.

When ferrite phase shifters are employed, an additional complication arises at high rf power levels. This complication is due to the dependence of the attenuation constant in a ferrite medium on the rf magnetic field. Below a critical value of rf magnetic field the attenuation constant is independent of the magnetic field, and above this critical value the attenuation constant increases when the rf magnetic field increases. In the case where one is dealing with a ferrite-loaded section of infinite length, the rf magnetic field is uniform in the axial direction and is simply related to the incident power level. However, in case of a ferrite phase shifter (the ferrite-loaded medium is finite), one expects a standing wave to be present along the length of the device and the rf magnetic field not to vary uniformly along the axis. This in turn implies that for a given amount of power transmitted there can be points within the ferrite phase shifter where the rf magnetic field exceeds the value that would exist for the same power transmitted in the case of an infinite-length ferrite section. Since the load impedance will clearly influence the standing-wave pattern in the phase shifter, it is clear that the critical value of the rf magnetic field can be expected to depend on the load impedance. Normally, the threshold level–the power level at which the critical value of rf magnetic field is reached–is specified for the case where the phase shifter is looking into a matched load; however, use in a phased array requires that the threshold level be known when the load is not matched.

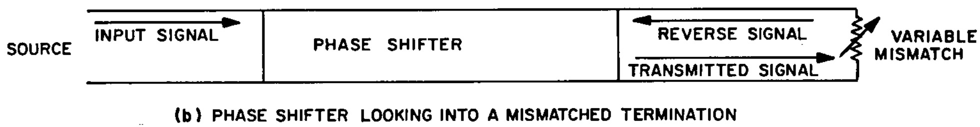
The object of this study is to present the effects of load VSWR on the performance of ferrite phase shifters so that a reasonable phase-shifter specification can be set for a given array. Prime consideration will be given to the effect of load VSWR on the threshold level. Since even in the case of an infinite-length ferrite section the relationship of the rf magnetic field to incident power is determined by the particular ferrite transmission line employed, data will be presented on several different models of ferrite phase shifters.

GENERAL BACKGROUND

Consider an individual phase shifter located within a phased array as shown in Fig. 1a. When the array is in the transmitting state, there will be a signal from the source incident on the phase shifter, a signal transmitted from the phase shifter, and a reverse signal traveling toward both the phase shifter and the source. This reverse signal is produced in an array by a combination of element VSWR and coupling from adjacent radiating elements. The magnitude and phase of the coupled signal depend on scan angle, position



(a)



(b)

Fig. 1 - Signals incident on a phase shifter located within an array and the signals incident on a phase shifter looking into a mismatched termination

of the radiating element within the array, and the array amplitude taper. By use of a variable phase and mismatch termination as shown in Fig. 1b, the effect of coupling on the phase shifter can be simulated. In this case the reverse signal is produced by the mismatched termination.

Let us start by considering how the behavior of the phase shifter is influenced by the variation in the mismatched load for the case where the phase shifter is linear (i.e., below the threshold level).

Consider a section of transmission line (Fig. 2) containing a matched source, a phase shifter, and a mismatched termination separated by ϕ degrees from reference plane II, the phase shifter. Let the input signal at I have unit amplitude and a phase angle of 0 degrees, T be the signal at II traveling from the phase shifter to the termination, and Γ_ℓ be the reflection coefficient of the mismatched termination. The signal traveling toward the source at II is designated by ρT, where $\rho = \Gamma_\ell e^{-2j\phi}$. The scattering relations for the section of line containing the phase shifter are

$$\begin{bmatrix} R \\ T \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} 1 \\ \rho T \end{bmatrix},$$

from which

$$T = S_{21} + S_{22}\,\rho T,$$

whence

$$T = \frac{S_{21}}{\left(1 - S_{22}\rho\right)}, \tag{1}$$

where S_{21} is the transmission coefficient τ at I looking from I to II with a matched load at II, and S_{22} is the reflection coefficient Γ of the phase shifter at II looking toward I with a matched load at I.

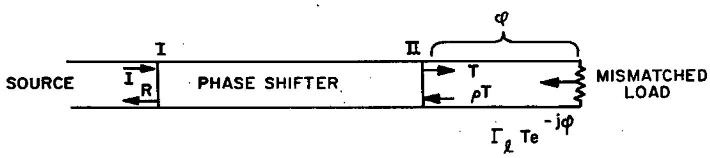


Fig. 2 - The model of a phase shifter and mismatched load employed in the linear region

Substituting for S_{21} and S_{11} in Eq. (1) gives the signal at II as

$$T = \frac{\tau}{1 - |\Gamma||\rho|\ e^{j(\gamma+\alpha)}},$$

$$= \frac{|\tau|\ e^{j\beta}}{1 - |\Gamma||\rho|\ e^{j\theta}},$$

where $\tau = |\tau|\ e^{j\beta}$, γ is the phase of Γ, α is the phase of Γ_ℓ plus $2\ \phi$, and $\theta = (\gamma + \alpha)$. It is also noted that $|\Gamma_\ell e^{j\alpha}| = |\Gamma_\ell| = |\rho|$. Thus,

$$T = \frac{|\tau|\ e^{j(\beta - \psi)}}{(1 + |\Gamma\rho|^2 - 2|\Gamma\rho|\ \cos\theta)^{1/2}}, \tag{2}$$

where

$$\tan\psi = \frac{-|\Gamma\rho|\ \sin\theta}{1 - |\Gamma\rho|\ \cos\theta}. \tag{3}$$

The phase difference ψ between the matched load condition and the mismatched condition is dependent on both Γ_ℓ and Γ.

If the extreme values of $|T|$ for a given τ are considered as a function of θ, it is readily seen from Eq. (2) that maxima and minima occur at $\theta = 2n\pi$ and $\theta = (2n - 1)\pi$, respectively, when $n = 0, 1, 2, 3, \ldots$. Consideration of Eq. (3) for $\theta = 2n\pi$ and $(2n - 1)\pi$ indicates that $\psi = 0$, so the phase would be that of the matched-load case when the extreme values of transmitted power are determined. Even though the phase shifters studied have nonlinear characteristics, this discussion indicates that transmission characteristics are influenced by the load mismatch.

EXPERIMENTAL INVESTIGATION

The basic measurement system used was a reflectometer setup incorporating a phase bridge. A variable-mismatch termination composed of a quadrature hybrid, ganged shorts, and a high-power load were used to terminate the transmission line. A schematic of the test instrumentation is shown in Fig. 3, and the variable-mismatch termination is discussed in Appendix A.

The insertion loss and the phase as a function of power level were determined for the matched termination case. Then a fixed-magnitude mismatch was set in the termination, and at each power level the phase of this mismatch was varied to obtain the extreme values of power transmitted ($|T|^2$ in the linear region). These points then determined two curves of transmitted power as a function of peak power level. The point on the curve at which the transmitted power starts to decrease indicates the threshold level with the load mismatch employed.

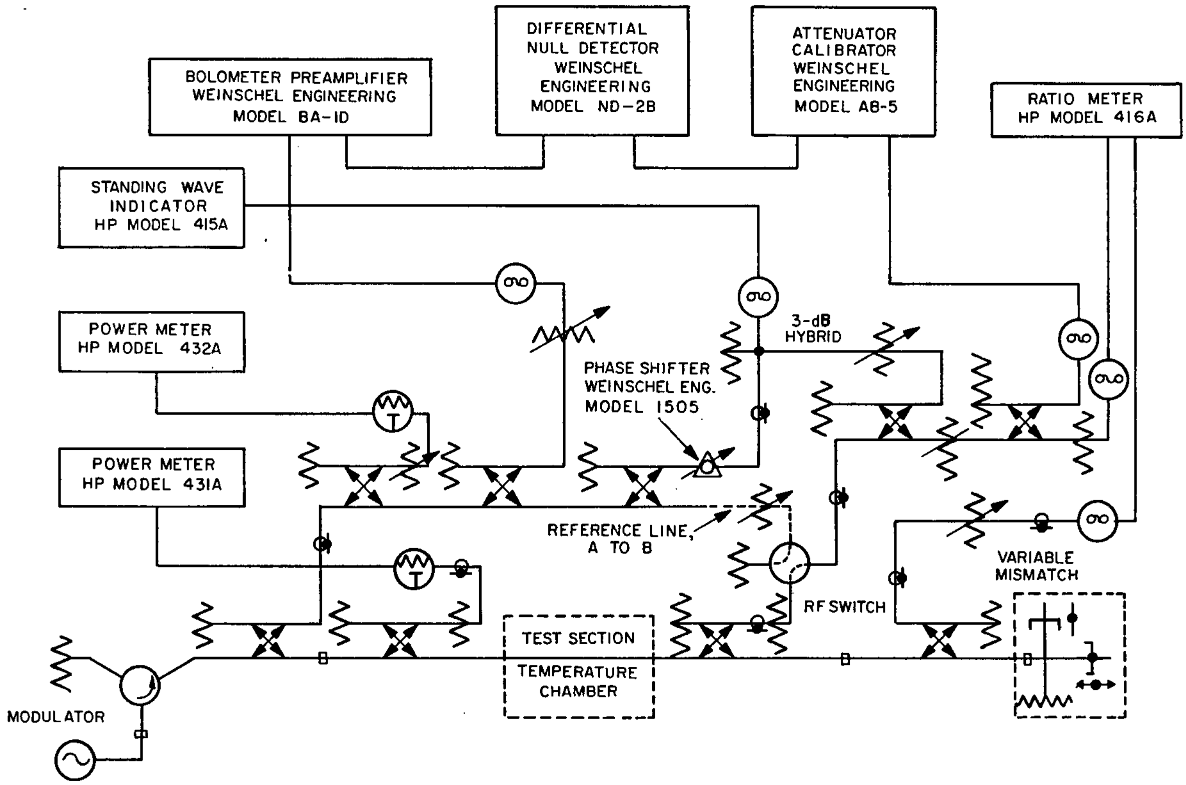


Fig. 3 - Schematic of test instrumentation

Three different models of nonreciprocal, digital, latching, ferrite phase shifters were studied. All four bits of each phase shifter were switched together. The two states corresponding to the two remnant values of the magnetic field were designated the positive and negative states. Since all three phase shifters used the same material, the differences encountered were due to the different ferrite-loaded transmission-line configurations.

Fig. 4 shows typical results obtained from measurements made on a phase shifter. Curve A represents the insertion loss of the ferrite phase shifter looking into a matched load. The data points determining this curve were obtained from several different runs and indicate the reproducibility of the data. Curves D and E represent the expected variation about A for the linear case when the termination VSWR is approximately 4:1. These curves were calculated from measured values of insertion loss and VSWR looking into a matched load. Curves B and C were determined experimentally and indicate the effects of the nonlinear properties of the ferrite device. Below 4 kW of peak power, the calculated curves D and E agree with the experimental curves B and C, indicating operation in the linear region. However, between 4 and 5 kW of peak power, curves B and C deviate from the calculated curves D and E, respectively. This deviation indicates the phase shifter has reached a new or premature threshold level relative to the matched-load case.

Another item of interest observed from Fig. 4 is the variation of the difference between the extreme values of transmitted power in the nonlinear region. In the region below 4 kW of peak power, the difference is constant as predicted by the calculated values in the linear region. However, in the nonlinear region the difference between the extreme values of transmitted power increases with increasing peak power. Thus the change of the difference between extreme values could also be used to determine the new threshold level.

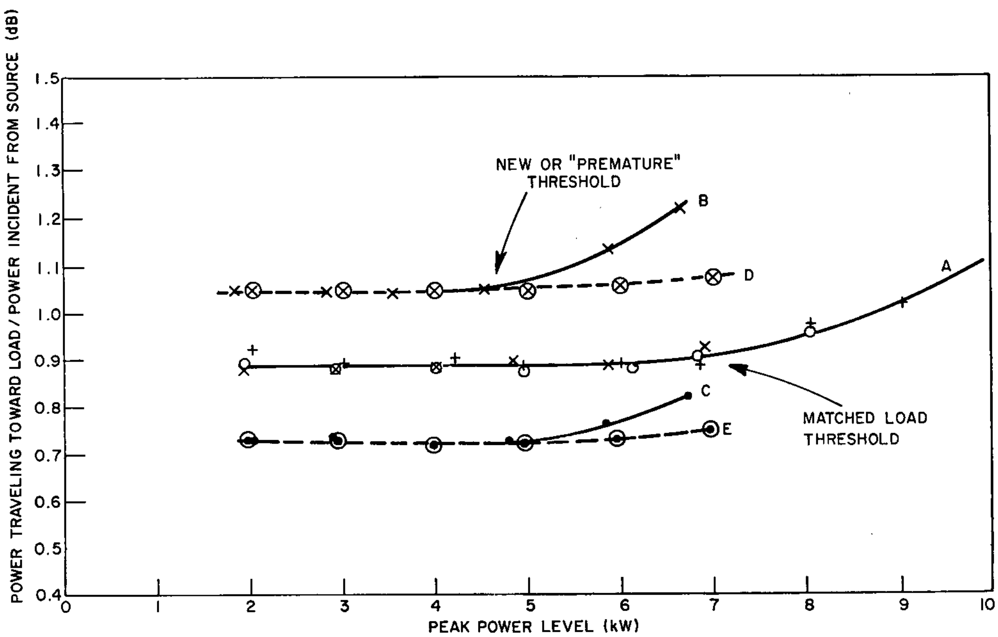


Fig. 4 - Comparison of experimental data obtained on ferrite phase shifter 3 looking into a mismatched load with results expected in the linear region test conditions were 3.1 GHz at 26°C, 1000 pps, 4-μsec pulse duration, loads VSWR 4.1, positive state

Data obtained for the first of three nonreciprocal, digital, latching, ferrite phase shifters (Unit 3) is shown in Fig. 5. Figure 5 shows the dependence of the extreme values of power transmitted on the peak power level for the phase shifter in the positive state and with load VSWR values of approximately 4:1, 3:1, and 2:1. The negative-state VSWR (corresponding to Γ of Eq. (1)) looking into a matched load was essentially constant at a value of 1.06:1 for peak power levels up to 7 kW peak. The positive state was chosen, since its threshold level looking into a matched load was lower than that of the negative state.

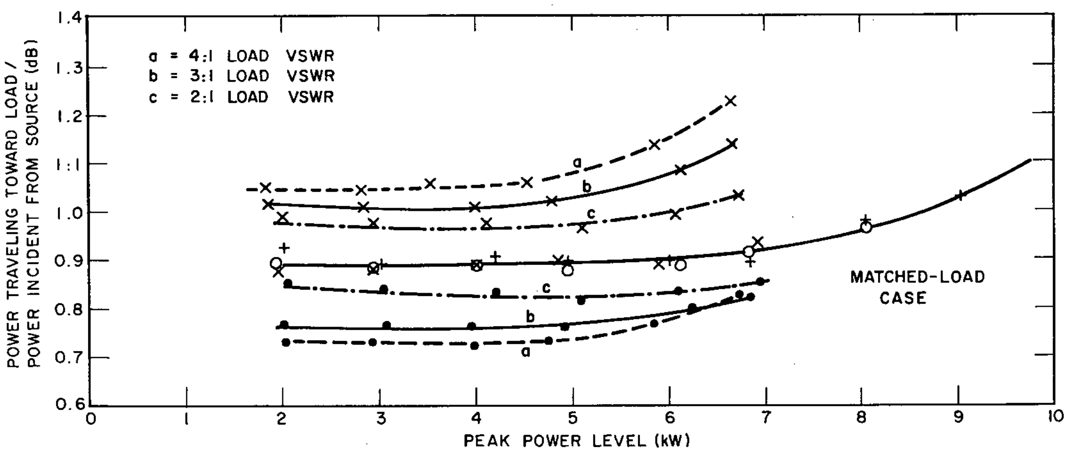


Fig. 5 - Power transmitted as a function of peak power level and load VSWR for phase shifter 3 test conditions were 3.1 GHz, 26°C, 1000 pps, 4-μsec pulse duration, positive state

Inspection of the threshold level for each of the extreme values of transmitted power indicates that the threshold level for the smaller amount of transmitted power occurs at a somewhat higher peak power level than for the larger amount of transmitted power. As the load VSWR increases, it appears that the threshold level decreases.

The difference between the extreme values of transmitted power increases with peak power level in the nonlinear region at a more rapid rate for higher values of load VSWR. While the curves denoting the extreme values of transmitted power go nonlinear at approximately the same peak power levels, the rate of decrease of transmitted power with peak power appears to be greater for the more lossy state.

The phase was measured for each state at each of the extreme values of transmitted power, and values obtained at each power level agreed within experimental error. Differential phase shift was determined at each power level and was essentially that of the matched-load case. Data obtained for the second nonreciprocal, digital, latching, ferrite phase shifter (Unit 12) studied is shown in Fig. 6. Again, the device VSWR (approximately 1.08) was essentially constant.

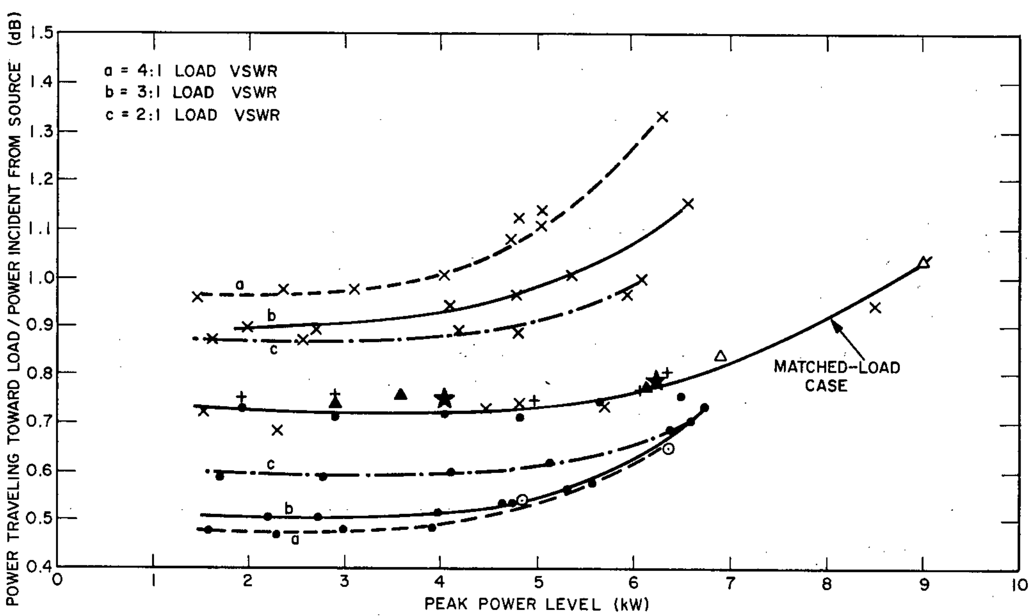


Fig. 6 - Power transmitted as a function of peak power level and load VSWR for phase shifter 12 test conditions were 3.1 GHz at 26°C, 1000 pps, 4-μsec pulse duration, positive state

The same trends with respect to threshold level as a function of load VSWR for the larger (4:1 and 3:1 VSWR) mismatched terminations are present in this unit as were present in Unit 3. Due to the difficulty in determining the threshold level for the lower 2:1 VSWR load, one cannot positively state that its threshold level is higher than that for the 3:1 VSWR load. Larger values for the difference between extreme values of transmitted power in the linear region can be attributed to the higher device VSWR and the greater absolute power traveling in the reverse direction. The load VSWR was the same in each case; however, the absolute power incident on the load differed due to the difference in insertion loss of the two phase shifters.

The phase measured for each state at each of the extreme values of transmitted power at given power levels agreed in the linear region. However, for the 4:1 and 3:1 load VSWRs, agreement for similar situations did not hold above 5 and 5-1/2 kW, respectively. The corresponding greater variations in differential phase shift may in part be due to a moding problem encountered in this phase shifter. Insertion loss spikes attributed to coaxial mode coupling were noticed earlier on Unit 12 and were corrected by locating a capacitor at an empirically determined point on the energizing lead to one of the toroids employed in the phase shifter.

The last of the three phase shifters employed a dielectric-loaded toroid as opposed to the air-filled toroid of the first two units. Data for this unit are found in Fig. 7. There was a slight increase in the VSWR from approximately 1:11 to 1:15 as the power level was increased from 1 to 16 kW. Again the same trends were present in regard to the threshold level as a function of load VSWR and difference between extreme values of transmitted power as were present in Unit 12.

Below 12 kW the phase measured at each state for each of the extreme values of transmitted power at a given peak power level agreed within experimental error. Again the differential phase shift was as would be expected considering the phase shift obtained under matched-load conditions.

SUMMARY

Data are presented illustrating the effect of load VSWR on the performance of three ferrite phase shifters. Generally, increasing the load VSWR decreases the threshold level relative to the matched-load conditions.

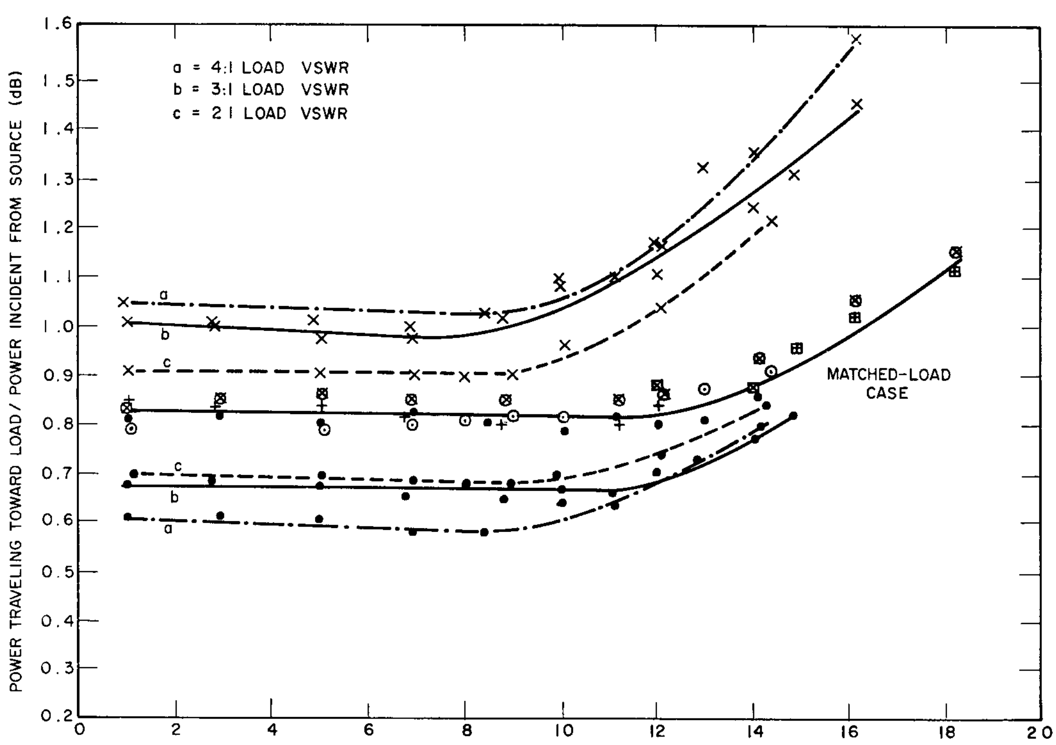


Fig. 7 - Power transmitted as a function of peak power level and load VSWR for phase shifter 7

Performance of these phase shifters was as expected in the linear region (below the threshold level); however, above the threshold level the device characteristics are changed by the phase of the signal traveling from the load.

Often the criterion used for a phase shifter employed in a scanning phased array is to have the threshold level twice the expected peak power level. Based on the results of the phase shifters tested, this criterion appears to be more than adequate for expected coupling equivalent to a load VSWR of 3:1 or less. However, testing the phase shifter under operating conditions with respect to equivalent power traveling from the load to the source would be preferred.

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Appendix A

VARIABLE PHASE-AMPLITUDE TERMINATION

The basic variable amplitude-phase termination employed is shown in Fig. A1. The ganged shorts move equal distances ($\delta/2$) but in opposite directions relative to reference plane A, while the location of plane A relative to the hybrid can be varied by changing the distance $x/2$. Inspection of a signal traveling through this device will show the required characteristics. For simplicity, assume the hybrid to have zero physical length and the phase constant to be β. When a signal of unit amplitude and zero phase is introduced at the input, the reflected signal will be

$$1/2\ e^{-j(\beta x-\delta+\pi)} + 1/2\ e^{-j(\beta x+\delta+2\pi)}$$

$$= 1/2\ e^{-j\beta x}\left(e^{j(\delta-\pi)} + e^{-j\delta}\right),$$

$$= 1/2\ e^{-j\beta x}\,(-2j\ \sin\delta),$$

$$= e^{-j(2\beta\ X/2 + \pi/2)}\ \sin\ 2\delta/2.$$

From this expression it is readily seen that the phase of the reflected signal is determined by the distance $x/2$ and the magnitude by the deviation $\delta/2$ from the reference plane. Thus the phase of the reflected signal can be adjusted independently of the amplitude and the amplitude adjusted independently of the phase.

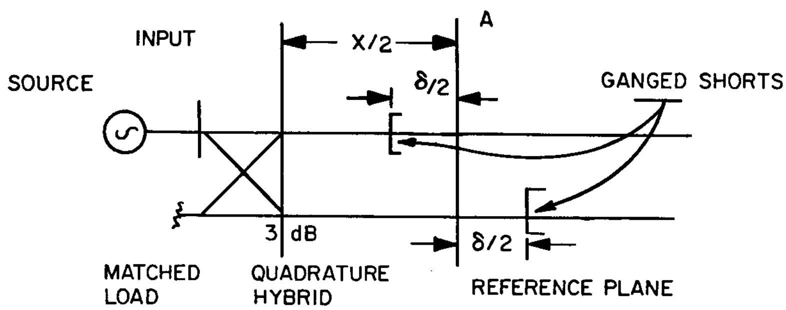

Fig. A1 - Variable-phase or/and -amplitude termination

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